AN IMPROVED NWP MODEL FOR FORECASTING THE PATHS OF TROPICAL CYCLONES

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ABSTRACT

An improved numerical prediction model for forecasting the paths of hurricanes and typhoons is presented. A constant circular vortex representing the tropical cyclone is translated each time step so that it is always centered at the cyclone's initial center point which is advected with the barotropic steering flow. The vortex flow advects the absolute vorticity of the steering flow thereby affecting the forecast speed and direction of movement of the vortex center. The vortex equations, the modified barotropic equation, and forecasts assuming both the 500-mb. flow and a vertically weighted mean flow as the steering flow are shown.

1. INTRODUCTION

Since 1956 the Joint Numerical Weather Prediction (JNWP) Unit has employed operationally over different periods two models for predicting the paths of tropical cyclones. Both models depended on the 500-mb. barotropic forecast. The first model, which was designed by Hubert [1], was employed from 1956 through 1958. The forecast path of the tropical cyclone resulted from tracking its center as a minimum stream function value in the 500-mb. barotropic forecast. The initial analysis for this forecast was a conventional 500-mb. height analysis. The second model, engineered by the author [2, 3], was employed from 1959 through 1960. The tropical cyclone was eliminated from the initial 500-mb. height analysis by discarding 500-mb. data in the immediate region and analyzing for a steering wind. The steering wind was determined from two or more most recent position reports of the cyclone eye. The initial position point of the cyclone eye was tracked in the 500-mb. forecast as the cyclone's forecast path.

Both forecast models exhibited serious deficiencies. The first model provided for interaction between the cyclone vortex and its steering current. However, insufficient initial 500-mb. data in the region of the cyclone plus difficulties in representing and maintaining a small vortex in a relatively coarse grid frequently resulted in incorrect direction of movement and resultant rapid deterioration of the forecast. The second model provided for proper direction of movement in the early period of the forecast but the absence of interaction between the vortex and the steering current greatly compromised the value of the forecast for periods exceeding 36 hours.

2. AN IMPROVED MODEL

Without many sacrifices and with some specific gains the best features of these two previous operational models have been incorporated into one hurricane and typhoon forecasting model, much in agreement with the ideas advanced by Musuda and Itoo [4], Morikawa [5], and Adem and Lezama [6]. The assumption of the barotropic flow as the steering current for the tropical cyclone is retained. Also, the vortex of the tropical cyclone is eliminated from the initial height analysis and a steering wind is analyzed in the region of the cyclone. The tropical cyclone is represented by a constant circular vortex stream described in terms of the cyclone's eye radius, maximum wind speed, and outside mean radius; information concerning these terms is available at or near the time of the initial analysis from aircraft reconnaissance and other data and analyses. The initial center point of the tropical cyclone is tracked in the barotropic flow and the vortex is mechanically moved so that it is always centered at this point for the purpose of employing its flow to advect the absolute vorticity of the barotropic flow. Deformation of the steering flow by the vortex and translation of the vortex are accounted for by this model. Asymmetry of the vortex at the initial time is not accounted for and deformation of the vortex or changes in its circulation during the forecast are prohibited.

The general equation for defining the vortex [7] is:

$$v = cr^n \tag{1}$$

in which v is tangential wind speed, c is a constant, r is radial distance from the center of the vortex, and n is a

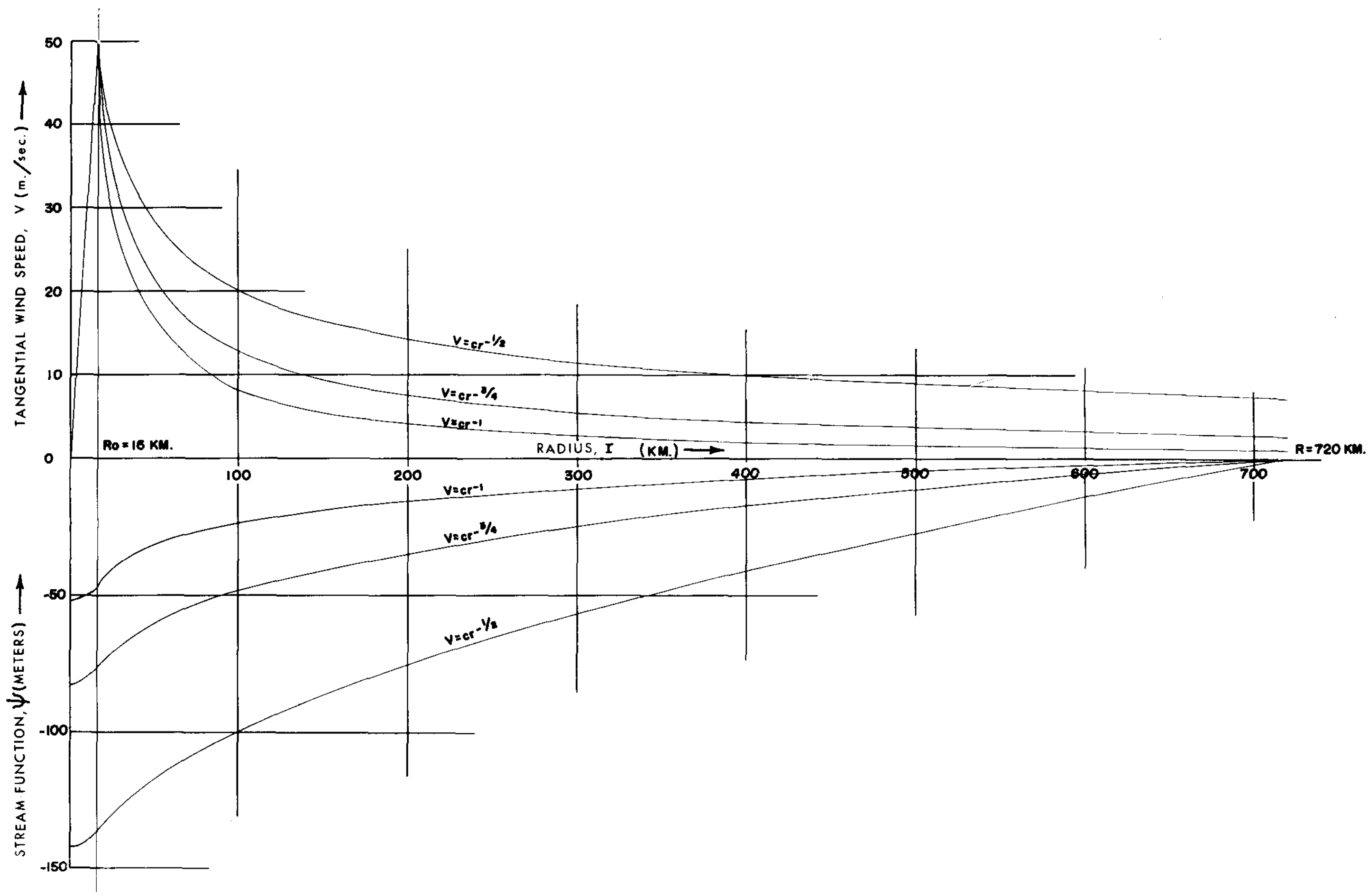

FIGURE 1.—Tangential wind speed and stream function curves for the several definitions for the region outside the vortex eye. Maximum wind speed, 50 m. sec.$^{-1}$; radius of the eye, 16 km.; outside radius, 720 km.

number in the range of -1 to 1. By assigning realistic values [8, 9] to n for a tropical cyclone, such as $n=1$ inside the cyclone eye and $n=-5/8$ from the edge of the eye outward, we then define a tangential wind speed profile as:

$$\left.\begin{aligned} v&=c_1 r, & 0\leq r\leq R_0 \\ v&=c_2 r^{-5/8}, & R_0\leq r\leq R \end{aligned}\right\} \qquad (2)$$

where R_0 is the radius of the cyclone eye and R is an outside mean radius of the cyclone circulation. In addition to geographical location of a tropical cyclone eye, observations of eye radius and maximum wind speed are made available by reconnaissance aircraft. An outside mean radius of circulation can be measured from a surface pressure analysis of the tropical cyclone. By assigning the maximum tangential wind speed, v_m, to the edge of the eye we can evaluate the constants c_1 and c_2 of equations (2). Since tangential wind speed, v, can be considered as the derivative of a stream function with respect to radius, then after integrating and assigning a value of zero to the stream function at the distance, R, from the vortex center, we have expressions for the vortex stream:

$$\left.\begin{aligned} \psi_1(r)&=\frac{v_m}{2R_0}[r^2-R_0^2]+\psi_2(R_0), & 0\leq r\leq R_0 \\ \psi_2(r)&=\frac{8}{3}v_m R_0^{5/8}[r^{3/8}-R^{3/8}], & R_0\leq r\leq R. \end{aligned}\right\} \qquad (3)$$

As indicated in equations (3), ψ_1 is assigned to be equal to ψ_2 at the distance R_0 from the vortex center. Figure 1 is a plot of tangential wind speed and stream function curves for a typical hurricane with respect to values of v_m, R_0, and R, and $-1\leq n\leq -1/2$ in equation (1) for the region $R_0\leq r\leq R$ of the vortex and $n=1$ for the region $0\leq r\leq R_0$ of the vortex. From these curves it is seen that tangential wind speed does not go to zero at the outside radius of the vortex. However, this appears to be only a minor discrepancy since the vortex stream values computed and employed in the forecast equation are at the points of a grid which has a mesh length of 381 km.

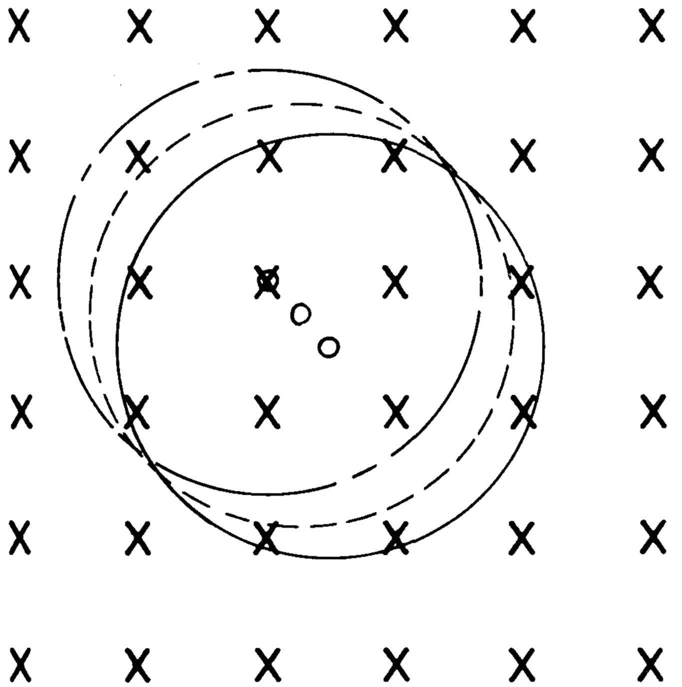

FIGURE 2.—Grid representation of the vortex with eight or more grid point stream values. Outside radius, $R > \sqrt{10}/2$ grid lengths.

at 60°, the true latitude of the polar stereographic map projection. Consistent with the size of the mature hurricanes and typhoons being represented, the outside radius of the vortex is specified to be greater than $\sqrt{10}/2$ grid lengths (see fig. 2). Therefore, eight or more grid point stream values other than zero immediately surround the vortex center and the effects of fictitious anticyclonic shear resulting from the methods of application are far removed from the crucial center point being tracked as the forecast.

The modified barotropic forecast equation employed is:

$$(\nabla^2 - K\bar{\eta})\frac{\partial\bar{\psi}}{\partial t} = J(\bar{\eta},\bar{\psi}+\psi)+\bar{\eta}G \tag{4}$$

in which K is a constant; $\bar{\psi}$ is the barotropic stream or steering flow; $\bar{\eta}$ is the absolute vorticity of the barotropic or steering flow; ψ is the vortex stream function; t is time; and $\bar{\eta}G$, which does not include the vortex stream function, ψ, is a combined friction and terrain term. By defining the total barotropic stream function as $\bar{\psi}+\psi$, the sum of a steering stream function and a vortex stream function, respectively, we see that there are two advection terms missing from the Jacobian of equation (4). The first is $J(\zeta,\psi)$, the advection of relative vorticity of the vortex by the vortex stream flow, which is approximately zero since the vortex is defined as circularly symmetric and constant in time. The second is $J(\zeta,\bar{\psi})$, the advection of the relative vorticity of the vortex by

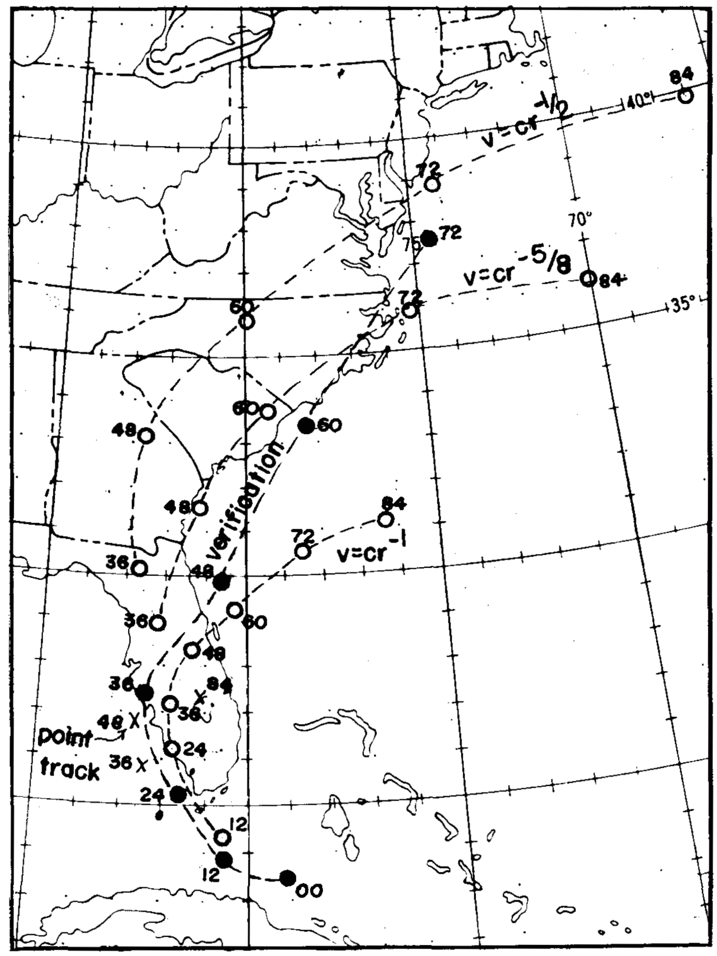

FIGURE 3.—Forecast tracks (open circles) for hurricane Donna from 1200 GMT September 9, 1960, made with varying wind speed profile definitions. Solid circles show the verification track. X's show forecasts made by previously used point tracking model.

the steering flow, which is accounted for in the model by mechanically translating the vortex stream each forecast time step thereby complementing the barotropic forecast equation (4).

3. FORECASTS AND CONCLUSIONS

A number of experimental forecasts were computed for 1959 and 1960 hurricanes and typhoons varying the values of maximum wind speed, radius of the eye, outside radius, and definitions of wind speed profile. Figure 3 shows the effects of the several different wind speed profile definitions with the vortex defined the same for each forecast. Included for comparison with no vortex is a track of the initial center point of the hurricane in the 500-mb. barotropic forecast steering flow. The effects of varying maximum wind speed, eye radius, and outside radius within the limits of observational accuracy and measurement in defining the vortex are relatively less

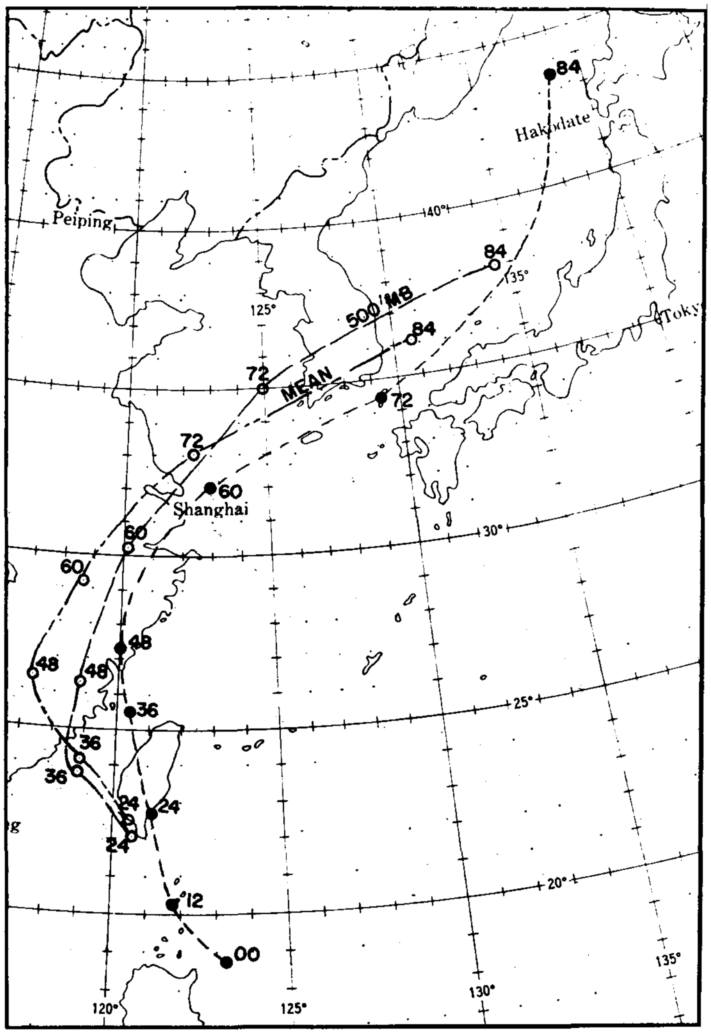

FIGURE 4.—Forecast tracks (open circles) for typhoon Betty from 1200 GMT, May 25, 1961, both for $v=cr^{-5/8}$, using different initial height analyses. Solid circles show verification track.

important to the forecast than the tangential wind speed profile definition. The eye radius is more critical than maximum wind speed or outside radius because it is least accurately observed or measured and a relatively minor variation in its magnitude constitutes a large percentage change in value. Figure 4 shows two forecast tracks for the same wind speed profile and vortex definition. For one forecast the 500-mb. barotropic steering was employed. For the other a vertically weighted mean height was employed as the initial height analysis for the barotropic forecast. The two forecasts agree reasonably well. Definitive conclusions as to the relative merits of one initial height analysis over the other cannot be drawn from comparing only these two forecasts. The vertically weighted mean height was obtained by weighting equally 850-mb., 700-mb., 500-mb., and 300-mb. analyzed heights.

The forecast tracks computed with this model are considerably better than those computed with the just prevous JNWP Unit operational point tracking model. The best definition of wind speed profile outside the eye seems to be that for $n=-\frac{5}{8}$ as in equation (2). The action of the vortex on the steering flow and the fact that the vortex is never allowed to be eliminated by smoothings during the forecasts are positive contributions to the accuracy of the forecast track. Errors in the barotropic forecast influence the forecast tracks. Earlier difficulties in obtaining the desired steering flow for the vortex in the initial stream, required by the barotropic forecast model, have been recognized and most have been eliminated.

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